Heat and Moisture Transfer During Transportation of Shelled Peanuts

M. E. Casada, J. H. Young

Abstract. *A finite-difference model was used to predict the moisture migration in shelled peanuts during transportation in sealed railroad tank cars. The roof of the railcar received solar radiation heating during the day and radiative cooling at night. Energy and mass balances were used along with a simplified zone analysis of radiative heat transfer to determine the conditions in a headspace above the peanuts. The model agreed well with temperature measurements from three tests with an experimental railcar. The long-term moisture migration from the natural convection currents was not sufficient to cause any excessive moisture accumulation in the railcar. The model simulations indicated that the diurnal heating and cooling cycle in the headspace was the primary cause of moisture accumulation at the top of the railcar.*
***Keywords.** Moisture, Peanuts, Grain storage, Transportation.*

During the shipment of shelled peanuts in sealed railroad tank cars (railcars), there is a potential problem of moisture migration causing wet spots in the peanuts. This may be the same type of moisture migration problem that has been observed to cause wet spots in the storage of grains in storage bins (Ross et al., 1973) and which could be the cause of wet spots observed in the storage of farmers stock peanuts in warehouses (Smith and Davidson, 1982). When these wet spots occur in peanuts, there is a risk of degradation in the quality of the peanuts, making them unsuitable for human consumption. The moisture migration in grain bins is known to be caused by the transport of moisture in natural convection currents.

The need to determine the causes of moisture migration in shelled peanuts during transportation in railcars requires a model to predict moisture migration in the irregular-shaped railcars. This article is the second of two articles describing the development and application of such a model. This article extends the numerical model developed in the first article (Casada and Young, 1994) to include the affects of a solar-heated headspace. This article also describes the application of the model to the transportation of peanuts and compares the model's predictions to experimental data.

Moisture migration in railcars may be the result of natural convection air currents produced by temperature gradients in the peanuts, as well as a result of moisture diffusion. These natural convection currents will be greater for a severe case such as a noninsulated railcar loaded during hot summer weather with cold peanuts from refrigerated storage. When cold peanuts are loaded in the railcar in warm weather the outer layer of peanuts act as an insulator, which keeps the center of the peanut mass near the refrigeration temperature at which they were loaded. When a layer of warm peanuts develops along the walls of the railcar, the resulting warm (high moisture) air begins to rise while the cold air in the center of the peanuts begins to fall. A circulating natural air current system results. As the warm air flows down through the cold peanuts, moisture is transferred to the peanuts. Moisture may even condense from the air onto the peanuts if the peanuts are below the dew point temperature. When moisture migrates for a sufficient length of time, a wet spot will be formed. Solar heating of the headspace above the peanut bed will increase the heat being circulated into the bed and may increase the moisture migration because the warmer air will hold more moisture, which will eventually be transferred back into the peanuts.

The temperature and moisture content of grain are generally considered to be the most important factors in controlling quality during storage (Ross et al., 1973; Muir, 1973). It is important to keep the temperature, relative humidity, and moisture content in grain at levels that limit the growth of harmful microorganisms, particularly, the aflatoxin producing fungus, *Aspergillus flavus* (Ross et al., 1973; Christensen and Kaufmann, 1968). Moisture migration from natural convection currents induced by temperature gradients in stored grain is a well known problem caused by adverse temperatures during storage (Ross et al., 1973; Muir, 1973; Loewer et al., 1979; Pierce and Shelton, 1984; Wilcke and Van Fossen, 1986). As a result, aeration of stored grain (moving a small volume of air through the grain regularly to minimize the temperature gradients in the grain) is usually recommended (Loewer et al., 1979).

Temperature and moisture content are both important factors in peanut storage (Smith and Davidson, 1982).

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The authors are **Mark. E Casada**, ***ASAE Member Engineer***, Assistant Professor, Dept. of Agricultural Engineering, University of Idaho, Moscow; and **James H. Young**, ***ASAE Fellow Engineer***, Professor, Dept. of Biological and Agricultural Engineering, North Carolina State University, Raleigh.

Again, an important consideration is the prevention of aflatoxins from mold growth, which is a major problem in peanut handling and storage (Dickens and Hutchison, 1976). Diener and Davis (1977) found that the growth of *A. flavus*, and the resultant aflatoxin production, was greatest at temperatures between 25° and 35° C and at relative humidities above 85%. This corresponded approximately to peanut kernel moisture contents above 10% w.b. (wet basis) in this temperature range. These researchers also found that there is some danger of *A. flavus* growth on peanuts between 12° and 41° C with relative humidities above 83%. The safe storage conditions for peanuts were reviewed and illustrated on a psychrometric chart by Smith and Davidson (1982).

Sanders et al. (1981) studied quality deterioration in farmers stock peanuts from five warehouses with significantly deficient storage conditions. They found that moisture accumulation, especially from condensation in inadequately ventilated headspaces was one of the most serious storage problems. One result they encountered from this moisture accumulation was the growth of *A. flavus*. Smith et al. (1983) documented the temperature profiles in farmers stock peanuts in two warehouses during a nine-month storage period. Smith et al. (1985) also documented both the temperature and relative humidity in one of these warehouses during a five-month storage period. Mechanical ventilation was used with this warehouse to prevent excessive moisture accumulation.

Casada and Young (1994) developed a finite-difference model to predict heat and moisture movement in an arbitrarily shaped porous media such as peanuts in a railcar. That model accounted for moisture transfer by diffusion and convection. It allowed a temperature difference between particles and the surrounding air, which may be important with the relatively rapid temperature change at boundaries due to diurnal ambient temperature change and solar heating. This temperature difference was taken into account with a two-energy equation model, which used one energy equation for the particles (solid matrix) and a separate energy equation for the interstitial air.

The objective of this research was to develop a mathematical model to predict transient moisture migration, from diffusion as well as natural convection currents, in sealed railroad tank cars partially filled with shelled peanuts when the walls are subjected to diurnally varying temperatures and the roof to a diurnally varying solar heating load, and then to evaluate the model with experimental data. The previously developed finite difference model (Casada and Young, 1994) for arbitrarily shaped porous media was adapted to incorporate the effects of the headspace with solar heating load.

Headspace Energy and Moisture Balance

The transition from laminar to turbulent natural convection for air in an enclosure between concentric cylinders seems to begin near a Rayleigh number of 10^5 (Farouk and Guceri, 1982), while it has been postulated to begin by a Rayleigh number of 1.4×10^7 in a square enclosure (Fraikin et al., 1980). The Rayleigh number in the headspace above the peanuts will be larger than either of these values whenever there is significant heating from the headspace walls; the relatively large dimensions of the headspace, as compared to the properties of air, result in large Rayleigh numbers even with small temperature differences (below 1° C).

Because of the turbulence of the headspace air and the difficulty of modeling turbulent natural convection, a well mixed airspace was assumed for both temperature and moisture conditions. The energy balance shown in figure 1 yields the following equation for the temperature of the headspace air:

$$(\rho c)_a V_H \frac{\partial T_H}{\partial t} = h_w A_w (T_w - T_H) + h_r A_r (T_r - T_H)$$
$$+ \sum_{\substack{\text{surface} \\ \text{nodes}}} h_s A_{s,n} (T_{s,n} - T_H) + \dot{m}_b c_a (T_i - T_o) \qquad (1)$$

In dimensionless variables, this becomes:

$$\frac{\partial \theta_H}{\partial \tau} = Nu_w(\theta_w - \theta_H) + Nu_r(\theta_r - \theta_H)$$
$$+ \sum_{\substack{\text{surface} \\ \text{nodes}}} Nu_s(\theta_s - \theta_H) + \dot{M}_b(\theta_i - \theta_o) \qquad (2)$$

Energy balances on the roof and wall give:

$$(\rho c)_r t_r \frac{\partial T_r}{\partial t} = h_{ri}(T_H - T_r) + h_{ro}(T_{amb} - T_r) + \alpha_{ro} I_r$$
$$- \varepsilon_{ro} \Delta R_r + SF_{rp} \varepsilon_{ri} \sigma (T_{ST}^4 - T_r^4) + SF_{rw} \varepsilon_{ri} \sigma (T_w^4 - T_r^4) \qquad (3)$$

and

$$(\rho c)_w t_w \frac{\partial T_w}{\partial t} = h_{wi}(T_H - T_w)$$
$$+ h_{wo}(T_{amb} - T_w) + \alpha_{wo} I_w - \varepsilon_{wo} \Delta R_w$$
$$+ SF_{wp} \varepsilon_{wi} \sigma (T_{ST}^4 - T_w^4) + SF_{wr} \varepsilon_{wi} \sigma (T_r^4 - T_w^4) \qquad (4)$$

Equations 2, 3, and 4 were incorporated into the finite difference model for the peanut bed and were solved simultaneously at each time step to obtain the headspace air temperature, the roof temperature, and the wall

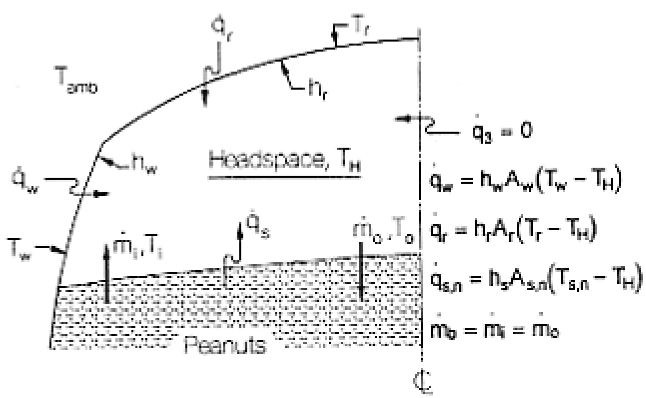

Figure 1–Energy balances for headspace air and walls.

temperature, using fourth-order Runga-Kutta integration. The radiation between the roof, walls, and top of the peanut bed was described with a simplified zone analysis (Ozisik, 1973) of the headspace radiation. The view factors required for this analysis were determined using view factor algebra (Ozisik, 1973). Radiation at the top surface of the peanut bed was calculated by summing the radiation over all surface nodes.

The humidity ratio of the headspace air was determined from the moisture balance in figure 2, which gives:

$$(\rho c)_a V_H \frac{\partial \overline{\gamma}_H}{\partial t} = h_{ms} A_s \rho_a \left(\overline{\gamma}_s - \overline{\gamma}_H\right) + \dot{m}_b\left(\overline{\gamma}_i - \overline{\gamma}_o\right) \quad (5)$$

or, in dimensionless variables,

$$\frac{\partial \Gamma_H}{\partial \tau} = Nu_{ms} A_s \rho_a \left(\Gamma_s - \Gamma_H\right) + \dot{M}_b\left(\Gamma_i - \Gamma_o\right) \quad (6)$$

The existing finite-difference model has a flow boundary condition available on the top surface that allows for airflow out of the porous medium into the headspace and vice-versa ($\dot{m}_i$ and $\dot{m}_o$ in fig. 1). Heat transfer between the headspace and the top of the peanut bed was described with a convective heat transfer coefficient (through q_s in fig. 1). The moisture transfer at the interface was similarly described with a convective mass transfer coefficient (as $\dot{F}_s$ in fig. 2). A 17 × 17 node mesh was generated for the peanut bed in the railcar as shown in figure 3.

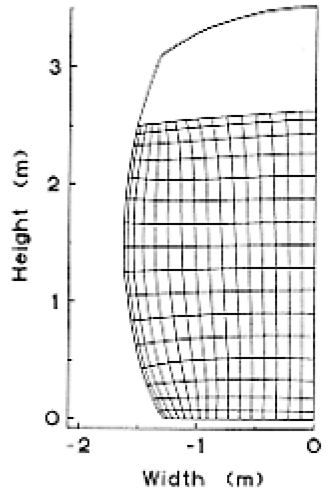

Figure 3–The 17 × 17 mesh for left half of the railcar (m).

Experimental Methods

A standard operating railcar was instrumented to measure the temperature of the peanuts and air and the relative humidity of the air during shipments of shelled peanuts from southern Georgia to Portsmouth, Virginia. One interior compartment of the car contained two temperature sensors and two humidity sensors located as shown in figure 4. In addition, one temperature sensor and one air speed sensor were located on the outside of the railcar. The temperature sensors were thermistor probes; the humidity sensors were thin-film polymer capacitor type; and the air speed sensor was a hot wire anemometer. All sensors were connected to battery operated automatic data acquisition units sealed in compartments inside the railcar that recorded the data hourly during the tests. The interior compartment was bounded by similar loaded compartments on both ends; thus, only two-dimensional effects existed in this compartment.

Three tests were performed using this instrumented railcar. In each test the shelled peanuts were loaded from a warehouse into the railcar and then the railcar traveled to its destination according to the usual procedures for these shipments. It typically required about two weeks for the railcar to travel to its destination (Portsmouth, Va.) and from three to five days waiting at the destination before unloading. Table 1 shows the railcar schedules for each of the experimental tests.

To prepare for loading, the railcar was moved into a covered shed adjacent to the warehouse. Peanuts for the tests were either taken from the warehouse (at the prevailing mean temperature, approximately 25° to 30° C) or from refrigerated storage (at approximately 10° C) depending on the type of test. The peanuts were loaded by belt conveyer into a hopper above the railcar, and then loaded into each compartment of the railcar through a 0.3 m diameter chute. Each of the four compartments

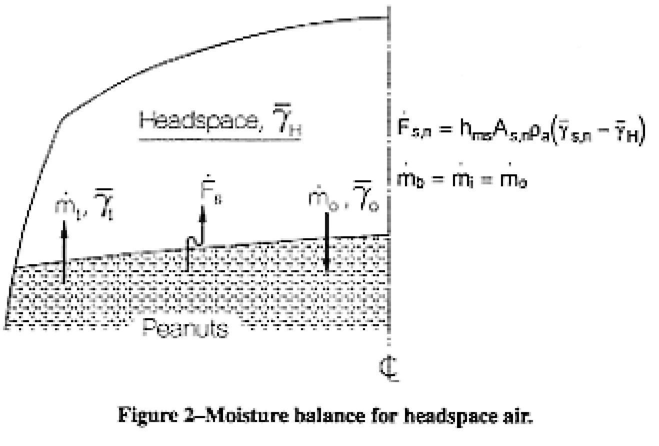

Figure 2–Moisture balance for headspace air.

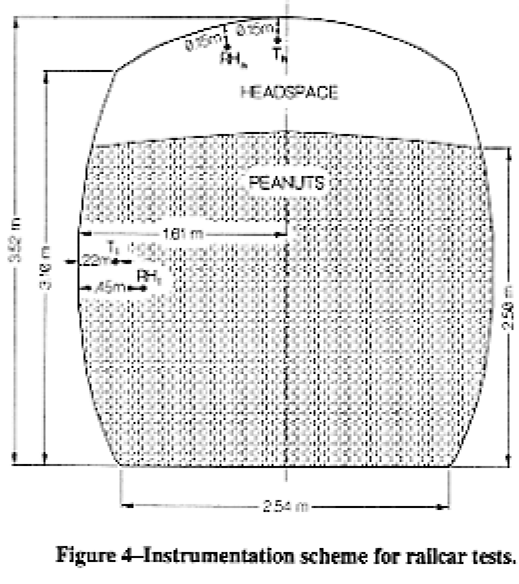

Figure 4–Instrumentation scheme for railcar tests.

Table 1. Schedules of railcar in experimental tests (time and date)

	Test No. 1	Test No. 2	Test No. 3
Finished Loading	13:00 6/18/87 Fitzgerald, Ga.	15:40 8/26/87 Albany, Ga.	12:00 9/23/88 Blakely, Ga.
Waycross, Ga.	6/27/87	9/9/87	9/29/88
Savannah, Ga.	22:25 6/30/87	9/13/87	10/1/88
Florence, S.C.	10:30 7/1/87	9/14/87	10/2/88
Rocky Mount, N.C.	20:25 7/1/87	9/14/87	10/2/88
Portsmouth, Va.	16:30 7/2/87	9/15/87	10/3/88
Began Unloading Portsmouth, Va.	14:00 7/8/87	08:30 9/23/87	13:30 10/8/88

required about 15 min to load. Table 2 shows the conditions for all tests.

The quantity of peanuts loaded into each compartment varied slightly because of the standard procedure used by the warehouse operators. However, the total variation in the amount of peanuts loaded was always less than 0.1% of the total volume of peanuts. The solar radiation incident on the railcar was not measured during the tests, so the amount of radiation was calculated from the data in ASHRAE (1981). This gave the amount of radiation for a clear day as a function of time of day. There was no measurement of cloudiness or other shading effects. When modeling experimental railcar tests, the reduction in radiation due to shading was determined by comparing the headspace temperature to the ambient temperature and then using a shading factor of 0.33 or 0.67 depending on the magnitude of the temperature difference.

The computer model was also used to simulate conditions in a hypothetical railcar that was subject to relatively severe conditions—this will be referred to as the standard test simulation. The hypothetical railcar in this simulation was loaded with shelled peanuts from refrigerated storage, at 4° C, and then subjected to a daily average maximum ambient temperature of 38° C and minimum of 21° C for the entire shipment time. For standard test simulations no shading was assumed.

Results and Discussion

The model was used to simulate conditions in the railcar during the three experimental tests. The temperature predictions of the model and, where possible, the relative humidity predictions of the model were compared to data collected in the railcars during actual shipments. In the first test, comparison of both temperatures and relative humidities was possible. In the other two tests, the relative humidity sensors were not operative due to being damaged in transit by the rough ride in the railcar.

Table 2. Conditions for experimental railcar tests

	Test No. 1	Test No. 2	Test No. 3
Type of Peanuts	No. 1 Mediums		
Initial peanut temp.	20° C	11 ° C	12° C
Initial moisture content	6.9% w.b.	7.0% w.b.	7.0% w.b.
Ambient temp. @ loading	36° C	33° C	35° C
Average ambient temp.	28.4° C	18.1° C	25.6° C
Minimum ambient temp.	18.1° C	4.3° C	9.7° C
Maximum ambient temp.	38.8 ° C	37.3 ° C	38.9° C
Final moisture content	6.9% w.b.	7.0% w.b.	7.0% w.b.

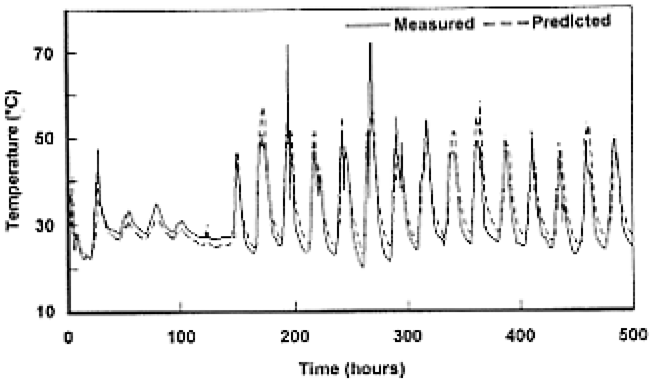

Figure 5–Measured and predicted headspace temperatures during test no. 1.

Heat Transfer

The measured temperature in the headspace in Test No. 1 is compared to the model's prediction in figure 5. There was good agreement between the measured and predicted temperatures throughout the test. From about day 2 through day 5, when there was little solar heating, headspace temperatures only increased a small amount during each day. During this period the model predicted a headspace temperature about 1° to 2° C lower than the measured values. This may have been due to a very small amount of solar heating through a thick cloud cover that did not trigger the solar heating term in the model to its smallest value (one-third of bright sunshine), but still raised the headspace temperature slightly.

Figure 6 shows the headspace temperatures for the middle portion of test no. 1 on a larger scale to clarify the comparison during the test. For most days the model's prediction followed the measured value quite well. During a few days the model predicted that the solar heating raised the headspace temperature as much as 7° C higher than the measured value. This may be because the schedule for the solar heating term in the model was not sufficiently refined to allow for the difference that exists between the condition of completely clear skies and that of slightly cloudy skies. The model apparently used the maximum solar heating of clear skies when there were enough clouds to lower the headspace temperature a few degrees. The predicted and measured headspace temperatures for test no. 2 are compared in figure 7. The headspace temperatures for Test No. 3 are compared in figure 8. The comparison is very

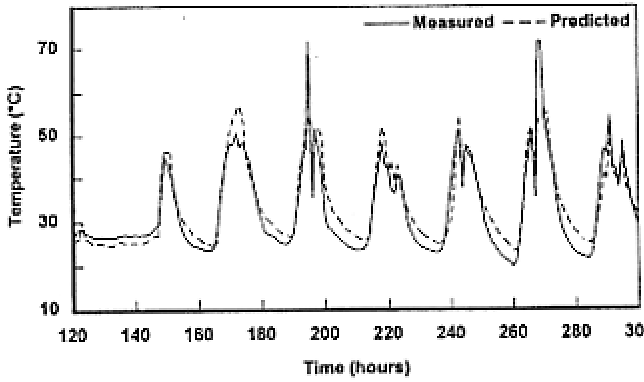

Figure 6–Headspace temperatures for middle portion of test no. 1.

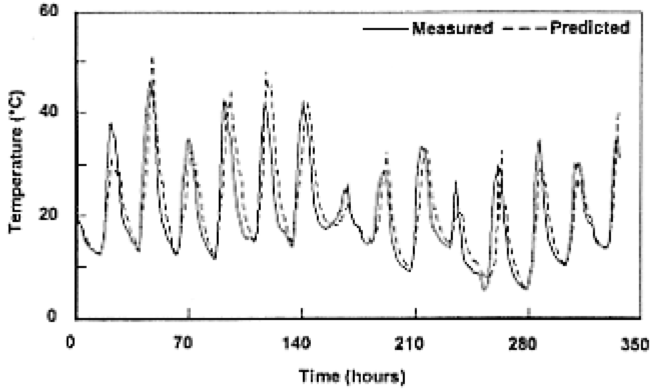

Figure 7–Headspace temperatures during test no. 2.

much like that for test no. 1. The main difference between the model's prediction and the measured temperatures is the occasional day where the model showed slightly greater solar heating than was indicated by the measured headspace temperature. Since this model's primary utility is predicting moisture migration problems under adverse conditions, nothing would be gained by refining the solar radiation load so that the model would predict individual data sets more precisely.

The temperatures near the side wall of the railcar are shown in figure 9. The model's prediction for both the air and peanut temperature are shown in comparison to the temperature measured with the temperature probe. There is a fairly consistent difference between the predicted and measured temperatures throughout the test, with the model prediction about 2° to 3° C lower than the measured temperature. There were three possible reasons for this difference: 1) there may have been a small amount of solar radiation on one side of the car causing slightly higher temperatures than predicted by the model, which does not account for solar radiation on the side of the car; 2) the assumed thermal properties of the side wall of the railcar may be in error; or 3) the convective heat transfer coefficient used on the outside of the railcar may be in error because only one component of air velocity was measured. The component of air velocity normal to the direction of the railcar movement was not measured, and it may have been significant at times when the railcar was not moving. The general reason is most likely not the solar heating since that would not be expected to supply such a consistent temperature difference. The possible solar

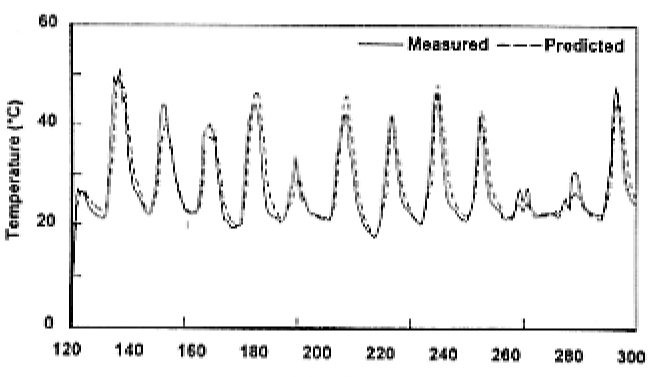

Figure 8–Headspace temperatures during test no. 3.

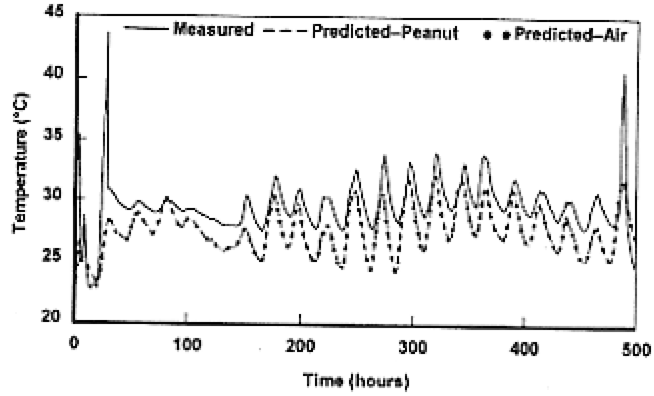

Figure 9–Measured and predicted temperatures near the side wall of the railcar in test no. 1.

heating on the side wall is likely to be the reason for the two specific occasions, at 24 h and at 480 h in test no. 1, where the measured temperature is briefly much higher than the predicted. The low prediction by the model most likely arises from the thermal properties used for the wall, as well as the heat transfer coefficient on the outside based on only the one component of air velocity.

Moisture Transfer

Figure 10 shows the model predictions of headspace air temperature, relative humidity, and moisture content (indicated by the dew point temperature) for four days of the standard test simulation. The moisture content cycle of the headspace air lagged the temperature cycle by only about 1 h, while the relative humidity cycle lagged by 7 h. The relative humidity cycle differs significantly because it was a function of air temperature and moisture content—both of which are varying—and not solely an inverse function of temperature as in similar situations with constant air moisture content. The air moisture content increased when the solar heating drove moisture from the peanuts to the warm air, which had a higher moisture holding capacity at the higher temperature.

Figure 11 shows the predicted and measured relative humidity in the headspace of the railcar. The predicted humidity followed a diurnal cycle similar to the measured humidity, but the measured relative humidity remained higher late in the day during most of the test, when the predicted value had dropped significantly. Thus, it appears that the peanuts did not reabsorb moisture as quickly as predicted by the model. Measured relative humidity values within the peanut bed (at RH_1) did not change significantly during the test—they remained at the equilibrium relative humidity corresponding to the peanut moisture content (which, of course, varied with the slight temperature change of the peanuts). The constant relative humidity was as expected and as predicted by the model; only peanuts near the top surface showed significant moisture content changes, due to their interaction with the heated headspace.

The model was used to predict the airflow, heat transfer, and moisture migration in the standard test simulations. Several other conditions have also been used to determine their effects on the model but the standard test simulations were the most severe conditions of the physically realistic possibilities. The simulations responded to parameter changes as expected from physical considerations. The

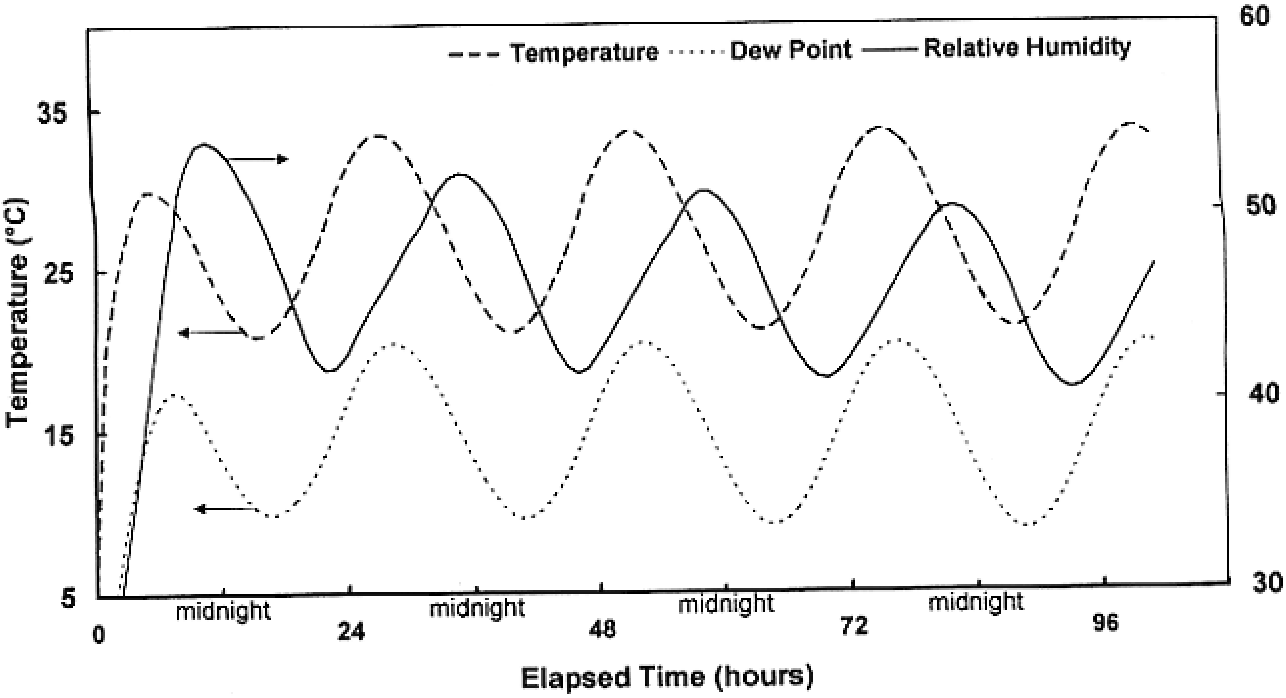

Figure 10–Temperature and moisture cycles in the headspace.

typical maximum length of time that peanuts would be expected to be in the railcar during shipment is about three weeks, so 20 days was chosen as the length of time for running the model to study the moisture condensation problem with the standard hypothetical test.

The two-energy equation model yielded differences between the peanut and air temperatures in the peanut bed. The differences were largest near the side boundaries, during the high midday heating periods, and at the top surface where radiation from the roof to the peanuts during the day kept the peanut temperature higher than the air temperature. This temperature difference at the top of the peanut bed was essentially limited to the surface and was as high as 0.7° C at noon. These temperature differences contributed slightly to driving more moisture from the peanuts during the day, which gave a greater potential for moisture condensation in the headspace at night. No direct condensation effects were seen in the headspace during any simulations with the model.

There are at least two places in the railcar where it was reasonable to expect moisture condensation due to short-term effects (i.e., due to the diurnal heating and cooling cycle) during transportation of peanuts. Both at the side boundaries and at the headspace the air attained a high moisture content during the day (note fig. 10) from equilibration with peanuts at the high daytime temperatures. When the peanuts and walls cool off at night, their temperature may drop below the air dew point temperature, causing moisture to condense. At the side boundaries the moisture in the small amount of interstitial air in the pore spaces is not likely to yield significant moisture condensation.

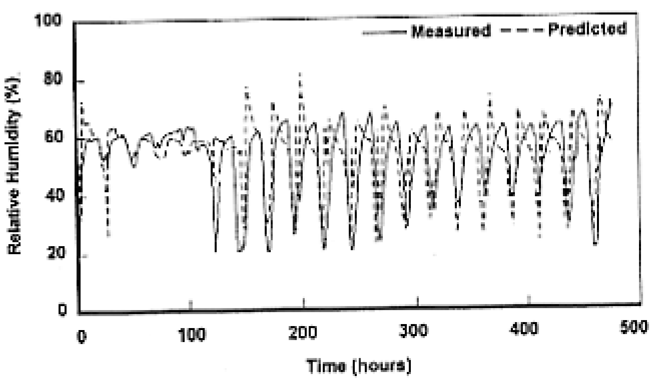

Figure 11–Headspace relative humidities for test no. 1.

The main moisture migration in the simulations was due to long-term effects (i.e., natural convection currents). The maximum increase in peanut moisture predicted by the model occurred at locations near the top peanut surface and side wall intersection. This location varied from 0.2 to 0.5 m from the intersection for the different tests. The maximum increase during the standard test simulation was 1.3% w.b. The increase during simulations of the experimental tests varied from 0.6 to 1.5% w.b. The maximum decrease in peanut moisture occurred on the top surface of the peanuts, with slightly greater moisture loss at the center of the top surface. The standard test simulation showed a maximum 1.5% w.b. decrease, while the simulations of experimental tests had maximums from 1.2 to 1.7% w.b. None of these moisture changes during simulations due to long-term effects were large enough to endanger the peanut quality during the three-week shipment times since they did not result in any unsafe conditions for the peanuts as described by Smith and Davidson (1982). Thus, while the same long-term moisture migration from natural convection was taking place in the railcar just as has been observed in grain bins, the three-week shipment times were too short for these effects to cause significant problems.

In the headspace, the model predicted that the peanuts reabsorbed moisture at night before any moisture condensed on the peanuts or walls. The comparison between the model and the measured relative humidity of the headspace in figure 11 shows that the relative humidity in the headspace did not decrease as the headspace cooled each day as fast as the model predicted. This is probably because the peanuts did not absorb moisture as fast as predicted by the model. If the moisture is absorbed more slowly by the peanuts than predicted by the model, then the headspace air dew point temperature could be high enough to cause condensation when the walls and peanuts cool off at night. After one of the railcar tests there were new water stains on the inside roof of the railcar indicating that moisture condensation had taken place. More basic data on moisture adsorption rates for peanuts, which is not currently available, would be required to further investigate these short-term moisture migration effects. Future research is needed to determine these absorption rates.

CONCLUSIONS

A finite difference model was modified to simulate the heat and moisture transfer in a railcar partially filled with peanuts. The headspace above the peanuts was treated as a well-mixed air space and the radiation in the headspace was described with a simplified zone analysis. The following conclusions were formulated from the results of this study:

- The model of the headspace predicted temperature and humidity with acceptable accuracy. Data on rates of absorption of moisture by peanuts is needed before model accuracy can be improved.
- The model predicts that the long-term moisture migration from natural convection and diffusion is not sufficient to cause moisture accumulation problems during typical three-week shipment times.
- Short-term moisture migration, due to diurnal heating in the headspace, which results in condensation of moisture on the peanuts and walls is the major moisture migration concern during transportation of peanuts in the rail cars.

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NOMENCLATURE

c = specific heat (J/kg K)
h = convective heat transfer coefficient (W/m^{2}K)
h_m = convective mass transfer coefficient (m/s)
k_a = thermal conductivity of air (W/m·K)
$\dot{m}_b$ = mass flow rate of air through the headspace (kg/s)
$\dot{q}$ = heat rate (W)
t = time (s)
t_w = wall thickness (m)
t_r = roof thickness (m)
A = surface area (m^2)
$\dot{F}$ = mass flow (kg/s)
I = solar radiation flux normal to surface (W/m^2)
L = maximum height of railcar (m)
ΔR_r = reradiation from roof to sky (W/m^2)
ΔR_w = reradiation from walls to sky (W/m^2)
T = temperature (K)
T_{amb} = ambient air temperature (K)
T_{ST} = average peanut temperature at top surface (K)
V_H = total volume of headspace (m^3)

Subscripts

a = air
i = air entering headspace
o = air exiting headspace
r = headspace roof
s = (top) surface of peanut bed, interface with headspace
w = headspace side wall
ri = inside roof surface
ro = outside roof surface
wi = inside wall surface
wo = outside wall surface

Greek Symbols

α_f = thermal diffusivity of air (m^2/s)
$\bar{\gamma}$ = humidity ratio ($kg_{H_2O}/kg_{dry\ air}$)
ρ = density (kg/m^3)
σ = Stefan Boltzmann constant = 5.67×10^{-8} $[W/(m^2K^4)]$

Dimensionless Variables

M_b = dimensionless headspace air flow rate = $(\dot{m}_b c_a L^2)/(k_a V_H)$
Nu = modified Nusselt number for headspace surfaces = $(hAL^2)/V_H$
Nu_m = modified Nusselt number for mass transfer = $(h_m AL^2)/(\alpha_f V_H)$
SF_{rp} = radiation shape factor from roof to peanuts
SF_{wp} = radiation shape factor from wall to peanuts
SF_{rw} = radiation shape factor from roof to wall
SF_{wr} = radiation shape factor from wall to roof
ϵ = solar emissivity
θ = $(T - T_o)/(T_w - T_o)$
α = solar absorptivity
τ = $(t\alpha_t)/D^2$ = dimensionless time
Γ = $\bar{\gamma}/\bar{\gamma}o$